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CYGNUS TRIGGER SYSTEM *

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Abstract

The Cygnus Dual Beam Radiographic Facility consists of two radiographic sources (Cygnus 1, Cygnus 2) each with a dose rating of 4 rads at 1 m, and a 1-mm diameter spot size. The electrical specifications are: 2.25 MV, 60 kA, 60 ns. This facility is located in an underground environment at the Nevada Test Site (NTS). These sources were developed as a primary diagnostic for subcritical tests, which are single-shot, high-value events. In such an application there is an emphasis on reliability and reproducibility. A robust, low-jitter trigger system is a key element for meeting these goals. The trigger system was developed with both commercial and project-specific equipment. In addition to the traditional functions of a trigger system there are novel features added to protect the investment of a high-value shot. Details of the trigger system, including elements designed specifically for a subcritical test application, will be presented. The individual electronic components have their nominal throughput, and when assembled have a system throughput with a measured range of jitter. The shot-to-shot jitter will be assessed both individually and in combination. Trigger reliability and reproducibility results will be presented for a substantial number of shots executed at the NTS.

I. GENERAL SYSTEM OVERVIEW

The Cygnus radiographic machines were originally designed for the Armando Subcritical Experiment (SCE) which was executed at NTS on May 25, 2004. The success in this experiment contributed to participation in a second test named Thermos. Thermos consisted of 12 high explosive shots which were conducted from February – May, 2007.

The machines were specially designed to fit in an underground tunnel laboratory and therefore were arranged in a linear fashion. Other requirements are collimated beams with a spatial separation of 60 degrees, and independently adjustable temporal separation. The layout of both machines in the underground U1a Complex at NTS is shown in Figure 1. The major components of each Cygnus source are: Marx generator, Pulse Forming Line (PFL), Water Transmission Line (WTL), Inductive Voltage Adder (IVA) which uses a Vacuum Insulated Transmission Line (VITL), and Rod Pinch Diode. Both machines have identical components except that the Cygnus 2 WTL is longer than the Cygnus 1 WTL.

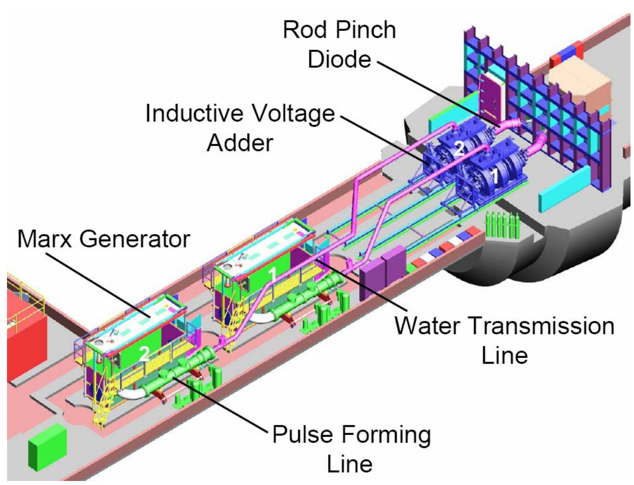

Figure 1. Cygnus layout in the U1a Complex at the Nevada Test Site.

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II. CYGNUS TRIGGER SYSTEM OVERVIEW

From end-to-end the trigger system for Cygnus uses the following components as shown in Table 1.

Table 1. Component specifications.

Component	Description	Manufacturer
NRT100	Optical to electrical transceiver	EG&G
DG535	Low voltage trigger generator	Stanford Research
Maxwell 40230	High Voltage trigger generator	Maxwell
Marx	High voltage energy storage	Maxwell/PI design
Wavepro 950	1GHz Digitizer	LeCroy

The NRT100 converts an optical trigger into a low voltage trigger signal. The DG535 trigger generator is used for timing adjustment. The Maxwell high voltage trigger output initiates breakdown of the Marx spark gaps which is the first step in firing Cygnus. A block diagram showing the layout of these components is given in Figure 2. There are several diagnostics for recording trigger signals. These signals are described in Table 2.

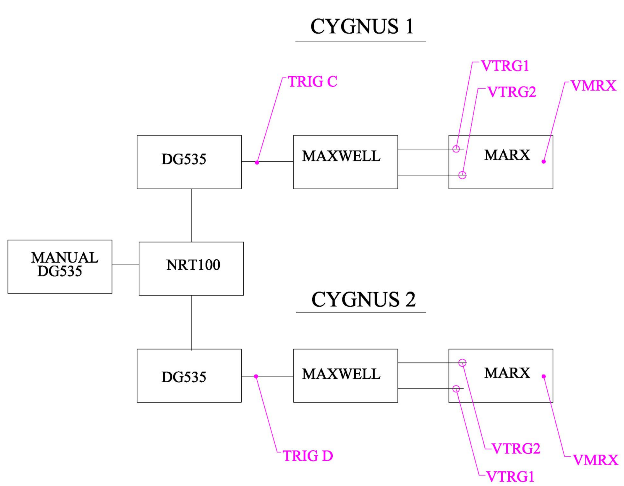

Figure 2. Block diagram of the major components in the Cygnus trigger system and related diagnostics.

Table 2. Trigger signals

Signal	Description
Trig C	DG535 output (on Cygnus 1)
Trig D	DG535 output (on Cygnus 2)
Vtrg1	Maxwell output
Vtrg2	Maxwell output
Vmrx	Marx output

There are five operational modes which are defined by the originating trigger pulse as follows.

A. T&F Mode

On a SCE there is a Central Fire Control Unit (CFCU) which supplies the originating triggers for all the diagnostics as well as the experimental package. These are called Timing & Firing (T&F) trigger pulses. The CFCU is located in a central command post several miles away from the experiment. In the T&F Mode an originating trigger pulse is sent, via a fiber optic cable, from the CFCU to the NRT100 trigger generators. This is the normal operational mode where Cygnus must be synchronized with other activities.

B. Manual Mode

The Cygnus Control Room is placed in a radiation safe location in the vicinity of the Cygnus sources. In the Control Room one rack contains the Cygnus Master Fire Control Unit (CMFCU). The CMFCU is an electronics chassis with front panel manual controls. It contains all of the features (e.g. interlock, charging, firing, and safeing) required to fire the Cygnus Marx without a computer interface. This mode was used to operate the prototype Cygnus machine before computer controls were installed. In the Manual Mode an originating trigger pulse is sent from the CMFCU to the Manual DG535. This mode is also used for system trouble shooting where a straightforward and local control methodology is desired.

C. PC Mode

The Cygnus Control Computer (CCC) may be located either in the Cygnus Control Room or uphole in a remote diagnostics trailer. In either case the CCC is used to automate Cygnus firing operations and monitor equipment conditions. The CCC can be used for operation in several configurations: a pre-shot test where only the Maxwell trigger generator is pulsed, a Marx test where the Marx output is directed to a resistive load located in the Marx tank, or a downline shot where the energy is routed to the diode. In the PC Mode an originating trigger pulse is sent from the CCC to the Manual DG535. This is the normal operational mode where Cygnus does not have to be synchronized with other activities. This mode is also used for system trouble shooting where it is desired to include the CCC as part of the testing.

D. DG535 Mode

The Cygnus Diagnostics Computer (CDC) may be located either in the Cygnus Control Room or uphole in a remote diagnostics trailer. The CDC includes software to control the DG535 units. In the DG535 Mode, an originating trigger pulse is sent from the CDC to the Manual DG535. This is yet another mode used for system trouble shooting.

E. Anomalous Mode

Note that the pulse derived from the Marx current monitors of both machines (Imrx) is combined and fed into the Manual DG535. In typical operations where the Marx generators are triggered through the normal trigger sequence, the Imrx feed-back trigger pulse occurs after the Marx has fired. Here the Imrx trigger pulse represents a second trigger which occurs subsequent to the intended trigger. Since the Marx is a single shot device such a trigger has no effect. For emphasis note the Imrx triggers will not refire a machine that has fired normally. For anomalous Marx conditions the Imrx trigger may offer a beneficial element for some conditions as described below.

1) No-fire

In this case the intended trigger pulse has failed to trigger a Marx. If the other Marx fires normally, its Imrx pulse may trigger the digitizers according to the fault location. In some situations it may also fire the anomalous Marx that had experienced a no-fire. However the possible scenarios for a no-fire are so numerous that the benefit of the Imrx trigger is diminished.

2) Pre-fire

The diagnostic digitizers are normally triggered via the trigger system sequence. However, if a pre-fire occurs, a Marx has discharged but the recording digitizers have not triggered. This makes determination of the root cause of the fault impossible. For shots immediately following Cygnus installation at U1a such problems were frequently encountered. Marx pre-fires occurred due to faulty terminations on the Marx resistors. Also there were problems with the Maxwell trigger generators prematurely breaking down and causing pre-fires. Since the normal trigger was not received and the diagnostics were not triggered, no data was available to help diagnose the problem. Using the Imrx feed-back trigger, this problem is solved. The digitizers are triggered by Imrx in the absence of a normal trigger signal and data for analysis of the fault is recorded.

In terms of trigger control authority and originating location see Table 3 for a summary of the 5 operational modes. The control authority is: external (T&F personnel), internal (Cygnus personnel), or automatic (Imrx). The originating location is: local (downhole near Cygnus) or remote (uphole).

Table 3. Trigger mode summary

Mode	Control	Location
T&F	External	Remote
Manual	Internal	Local
PC	Internal	Local or Remote
DG535	Internal	Local or Remote
Anomalous	Automatic	Local

III. UNIQUE FEATURES

A SCE uses many different diagnostics in addition to radiography, as well as an experimental package. Therefore it is required to synchronize system equipment in a countdown sequence. To this end a Process Control System (PCS) is used as a master control of all activities. Since a SCE is a high value, single shot event, a major function of this system is to stop execution of a test during the countdown if any faults are encountered. In addition the PCS has an important personnel safety function. There are many different hazards present such as laser radiation, high voltage, x-rays, and high explosives. The PCS is used to monitor these hazards and control excluded areas during an experiment. The exclusion area is swept and personnel are accounted for prior to all radiation operations. A brief overview of the PCS is described as follows:

- Intellution control and monitoring software is used to continuously monitor the conditions of the various equipment outputs and environment parameters.
- If conditions in one area are not correct, at the appropriate time an alarm is sounded and warning lights are activated.
- The countdown is held and signals dropped to a safe condition until the situation that held the event is corrected. The software is reset and a new count down is started.
- A software abort and a hardware abort feature are designed into the monitor system where operators of the different systems can stop the countdown through software or personnel can stop the countdown through activation of a scram switch.
- In the event of a scram switch (hard) abort the area must be re-swept.

The Cygnus machines also have a dedicated process control system which controls normal operations, halts execution for a fault mode, and manages hazards. It has four features to reduce exposure to pre-fire by limiting the time window that equipment is subject to a pre-fire. The fifth feature sends a critical hold to the PCS in case of a Marx pre-fire.

- A Ross relay is attached to the output of the Marx power supplies that charge the Marx capacitor bank. It is changed to an open state which enables the Marx charging at T minus 1 minute.
- A Marx output switch (swing arm) is connected to the resistive load position (28 ohm aqueous-salt resistor) when the Marx is

charging and switched over to the PFL center conductor late in the countdown sequence.

- A relay which enables high voltage in the Maxwell trigger generator is energized late in the countdown sequence.

- A Ross relay is connected to the Maxwell trigger generator output. This relay grounds the Maxwell output, which kills the trigger pulse, until late in the countdown sequence when it is opened. It is attached to the underside of the Marx lid as shown in Figure 3.

- If either Marx experiences a pre-fire a critical hold signal is sent to the Process Control system. This critical hold is initiated by the Imrx signal which occurs in time to safely abort the shot.

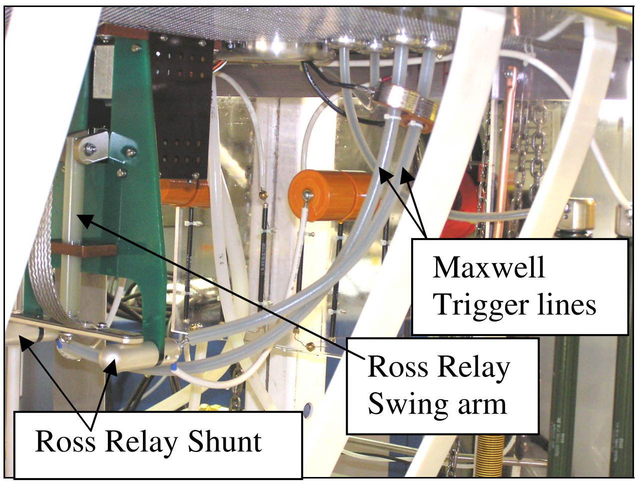

Figure 3. Ross Relay shunting Maxwell trigger generator output located underneath Marx lid.

The relay states are monitored by the PCS which uses Process Logic Control (PLC) software. The following is an example of the automated countdown for a shot and the sequence of events which take place to fire the Cygnus machines. This sequence of events is taken from the standpoint of the Cygnus Trigger System and does not consider the plethora of conditions and scenarios not associated with the trigger system. If any of the monitored status conditions are not met the countdown is held. At T minus 5 minutes the main PLC sequence begins. This command starts the monitoring and control of the PLC units underground. The first command, at T minus 5 minutes, lifts the Ross relay on the Marx charging power supply lines allowing the charging of the Marx (at T minus 1 minute). At T minus 10 seconds the swing arm is switched from the resistive load to the PFL load. At T minus 5 seconds the high voltage relay internal to the Maxwell Trigger Generator is enabled. At T minus 4 seconds the Ross relay that grounds the output of the Maxwell trigger generator is lifted (see Figure 3). The system will proceed to T minus 0 seconds unless an Imrx signal is fed back from either machine indicating a pre-fire. This generates a critical hold which is guaranteed at least up to T minus 1 second for any situation. The actual time is dependent on several variables. On Armando, the critical hold signal was valid to T minus 35 ms. Between T minus 35 ms and T minus 0 seconds the critical holds are not valid and the machines are vulnerable to firing even when faults occur. If a machine does pre-fire at any time, the Imrx feed-back signal will trigger the digitizers to permit diagnosis of the fault condition.

IV. JITTER ANALYSIS

The data from the Armando SCE series was used for the jitter analysis of the Cygnus trigger system. The components being analyzed are the Maxwell High Voltage Trigger Generators and the Marx Generators. Refer to Figure 2 for the Trigger system components and diagnostic signals. The DG 535 output (Trig C – Cygnus 1, Trig D – Cygnus 2) triggers the Maxwell trigger generator.

The Maxwell trigger generators are housed in separate Radio Frequency Interference (RFI) shielded racks located 2 ft from the ground end of their respective Marx tank. Each Maxwell trigger generator has 2 output cables, 24 ft long, which feed into the Marx spark gap network. The output is measured under the lid of the Marx via 2 Bergoz fast current transformers, one fast current transformer per cable (See Figure 4). These diagnostics are labeled Vtrg1 and Vtrg2.

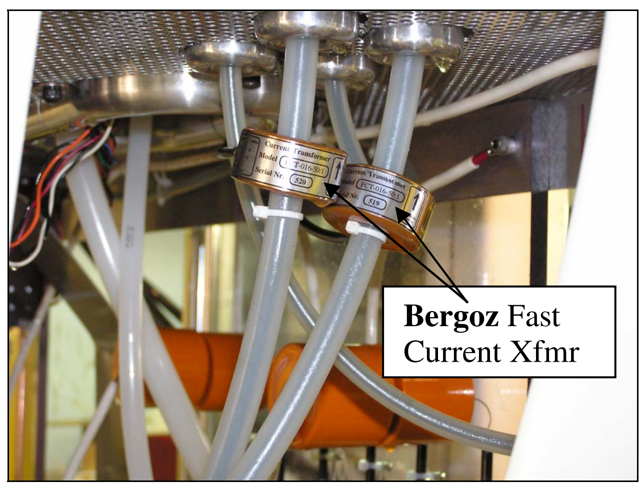

Figure 4. Bergoz fast current transformer (Diagnostic label Vtrg1&2) located underneath Marx lid on Maxwell trigger lines.

The Marx is hung from the tank lid via nylon straps. The lid lifts from the tank allowing access to the Marx via hydraulic jacks positioned at each corner. A pivoting swing-arm connects the Marx to a 28 ohm clamping resistor during the charge sequence, limiting the voltage at the output node of the Marx to ~53% of charge if fired into the clamp. Marx diagnostics consist of a Current Viewing Resistor (CVR) at the ground end, and a liquid resistive voltage monitor connected to the output plate at the high voltage end. The Marx CVR signal is labeled Imrx and the Marx resistive voltage monitor is labeled Vmrx. In summary, the diagnostic signals used to calculate jitter are Trig C – Cygnus 1 (Trig D - Cygnus 2), Vtrg2, and Vmrx. Sample signals for Cygnus 1 are given in Figure 5.

Trigger time is defined at the signal amplitude indicated by the arrows: $t_{Trig\ C}$ (10 v), t_{Vtrg2} (-0.2 kA), and t_{Vmrx}(-0.9 MV). Note that Vtrg1 and Vtrg2 are current transformer signals and therefore have units of kA.

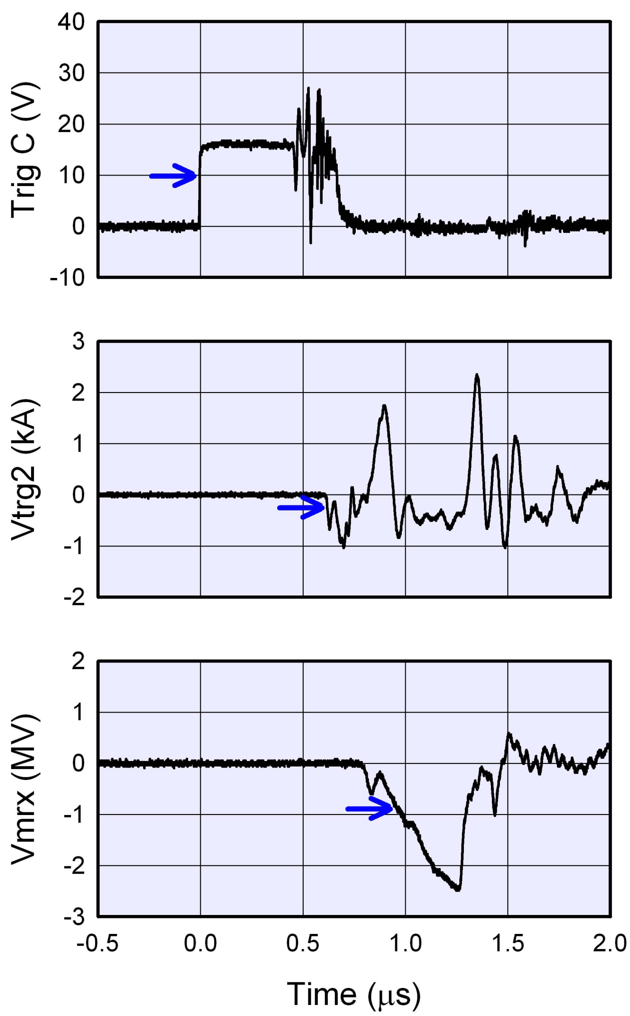

Figure 5. Cygnus 1 trigger time is defined at the signal amplitude indicated by the arrows: $t_{Trig\ C}$ (10 v), t_{Vtrg2} (-0.2 kA), and t_{Vmrx} (-0.9 MV).

For Cygnus 1, throughput calculations are as follows:
Maxwell throughput = [t_{Vtrg2} (-0.2 kA) - $t_{Trig\ C}$ (10 v)],
Marx throughput = [t_{Vmrx}(-0.9 MV) - t_{Vtrg2} (-0.2 kA)],
System throughput = [t_{Vmrx}(-0.9 MV) - $t_{Trig\ C}$ (10 v)].

Throughput calculations for Cygnus 2 are similar except replace “Trig C” with “Trig D”. A compilation of throughput results for the Armando shots is given in Figures 6 and 7. Mean, throughput and jitter are listed in Tables 4 and 5. The results are tabulated for two cases, Marx termination in a resistive load, and Marx termination into the PFL load.

The difference in the throughput of the Cygnus 1 and Cygnus 2 Maxwell trigger generators (20 ns for both load cases) is due to a Thyratron internal to the Maxwell unit. The throughput of each unit is within the manufacturers’ specifications listed as < 250 ns. The jitter results for the Maxwell on Cygnus 1 and Cygnus 2 into either load was ~ 1-2 ns which is minimal for our system and within the manufacturer’s specifications listed as < 3 ns.

The difference in the throughput of the Cygnus 1 and Cygnus 2 Marx generators (6 ns for the resistive load, 11 ns for the PFL load) is reasonable for a system with such a large number of spark gaps. Also the jitter results for the Marx on Cygnus 1 and Cygnus 2 into either load was ~ 4-5 ns, which is, minimal for our system.

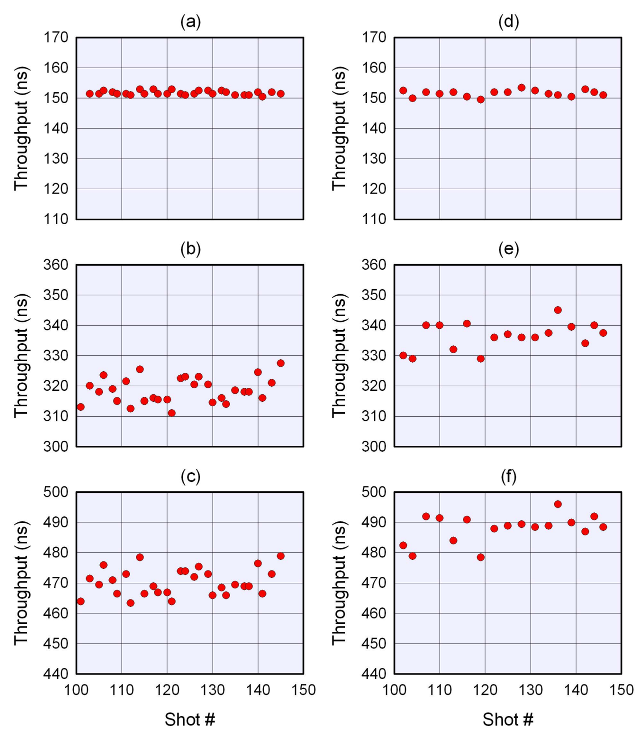

Figure 6. Cygnus 1 component and system throughputs. The left column is the case of Marx termination into the resistive load for the following elements: (a) Maxwell, (b) Marx, and (c) System. The right column is the case of Marx termination into the PFL load for the following elements: (d) Maxwell, (e) Marx, and (f) System.

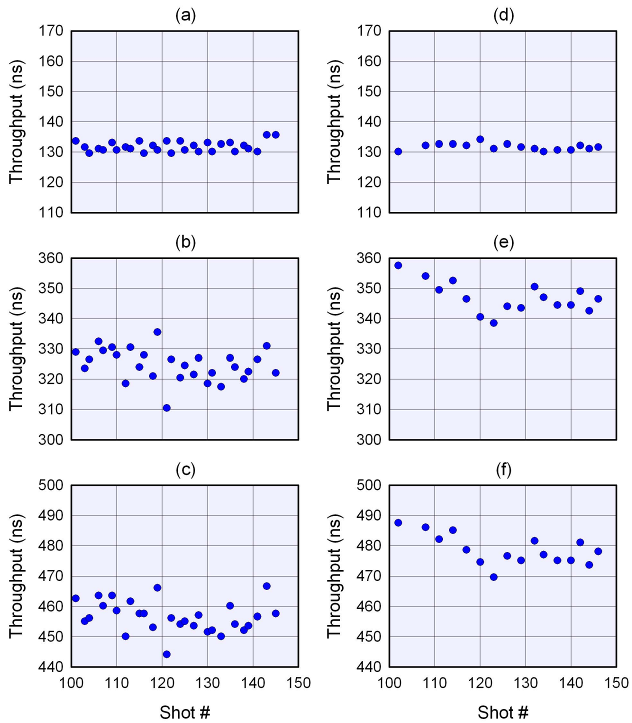

Figure 7. Cygnus 2 component and system throughputs. The left column is the case of Marx termination into the resistive load for the following elements: (a) Maxwell, (b) Marx, and (c) System. The right column is the case of Marx termination into the PFL load for the following elements: (d) Maxwell, (e) Marx, and (f) System.

Table 4. Cygnus 1 throughput time and jitter.

Component	Throughput Resistive Load (ns)	Throughput PFL Load (ns)
Maxwell	152 ± 1	152 ± 1
Marx	319 ± 4	336 ± 4
System	470 ± 4	488 ± 5

Table 5. Cygnus 2 throughput time and jitter.

Component	Throughput Resistive Load (ns)	Throughput PFL Load (ns)
Maxwell	132 ± 2	132 ± 1
Marx	325 ± 5	347 ± 5
System	457 ± 5	479 ± 5

V. SUMMARY and FUTURE IMPROVEMENTS

The Cygnus Trigger System was designed as a reliable, robust, low jitter system with added features to accommodate and protect the investment of a high value shot. For the Armando test series (Shots 100 -146) the Cygnus machines experienced zero pre-fires and zero no-fires. The intent of the original design of these machines was to use existing off the shelf, highly reliable components for creating production mode radiographs. The major source of jitter in the Cygnus Trigger System is the Marx spark gaps. With the original design the jitter of the spark gaps is considered acceptable. Note the chief source of jitter in the entire machine stems from the PFL main water switch. An attractive feature of the Marx spark gaps is that they use zero air and not SF_6 gas. SF_6 is a safety concern in an underground environment.

With the rapid advancements in technology and changes in application of the systems, the need for continuous improvement and upgrades is desirable. Laser triggered spark gaps are currently being developed at other laboratories and universities and would have inherently less jitter. A laser triggered spark gap with low jitter could improve this system as the current configuration is populated with 33 spark gaps in the Marx and 2 spark gaps in the Maxwell trigger generator. The laser triggered spark gaps also would require additional hardware and complexity possibly compromising an already reliable robust trigger system. While components comprising single points of failure cannot be eliminated from a given system, as many as possible of these singular components must be made redundant or eliminated altogether without compromising the reliability or functionality of the system. The system will be reviewed with each new application and changes made with the aforementioned concerns evaluated.

VI. REFERENCES

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